RESPONSE OF A MEDITERRANEAN RIPARIAN FOREST TO A 1 IN 400 YEAR FLOOD, OUVEZE RIVER, DROME-VAUCLUSE, FRANCE

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ABSTRACT

This study provides original data concerning the impact of an exceptional 400-year flood on the riparian forest of a six order French Mediterranean river. Both the restricting effects of the forest on the flood and the hydraulic behaviour of the forest during the flood were studied. Twenty-five per cent of the riparian forest was destroyed or profoundly altered as the flood waters enlarged the channel which was initially less than 200 m wide. However, the forest also reduced the flow capacity of the floodplain (lateral reduction of high water level). It also reduced lateral mineral fluxes (lateral reduction of sediment granulometry) and organic deposition (lateral reduction of coarse woody debris mass). However, the lateral extension and topographic accretion of the forest reduces the flood evacuation capacity of the bed and thereby increases the risk of flooding. Future legislation will have to take into account the nature of antropogenic activity in the area of the study. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

The hydrological regime of French Mediterranean rivers is characterized by contrasting behaviour, with low summer flow and two periods of high discharge during autumn and spring. The Ouvèze flood (Figure 1) of 22 September 1992 was one of the most serious hydrological catastrophes ever known in France. It was an early autumn flash flood, this being the most common period for violent storms in the Mediterranean region (Pardé, 1925; Pagney, 1988). The frequency of this event has been estimated as ‘greater than 100 years’ (Conseil Général des Ponts et Chaussées, 1992) and even as great as 400 years using the Gradex method (de Saint Seine, 1992). The peak flow was of the order of 800 to 1000 $m^3\ s^{-1}$ at Vaison-la-Romaine (Chastan *et al*., 1993). This event appears to have been the largest since the 17th century when the flood of 1616 destroyed the parapet of the Roman bridge at Vaison. That event, at the time, was described as a ‘great disaster’.

The 1992 flood was caused by very intense torrential rains falling on ground already saturated by previous rains and in a region of high relative relief. The rains fell in the Ouvèze catchment area between 10.25 and 11.45 hrs from a series of storm cells travelling in a northeasterly direction at about 60 $km\ h^{-1}$. Above Vaison the average rainfall totalled 90–95 mm but rain gauges recorded 300 mm at Entrechaux and 179 mm at Vaison (Figure 2a; Blanchet and Deblaere, 1993). Radar images indicated (Figure 2b) values between 200 and 250 mm over a 35 km area (Kapfer, 1993). Over a period of 18 min, very high rainfall intensities were 25·1 mm at Vaison and 26·6 mm in the Groseau catchment, a few kilometres upstream from Vaison (Figure 1b). The volume of rainfall was of the order of 50–55×$10^6\ m^3$. Loss of life, great destruction of buildings and equipment, especially in the urban reach of Vaison, and the flooding of thousands of hectares, made this a national catastrophe (Arnaud-Fassetta *et al*., 1993; Flageolett *et al*., 1993). The psychological impact on the local population prompted them, and the media, to seek an explanation for the amplitude and suddenness of this event. The deforestation of the upper catchment area was blamed, as was poor maintenance of river bank vegetation.

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Unfortunately, information on a floodplain forest response to a major hydrological event is rare. The aim of this paper is to describe and analyse active biogeomorphological processes and responses during a flood of this type for a Mediterranean river.

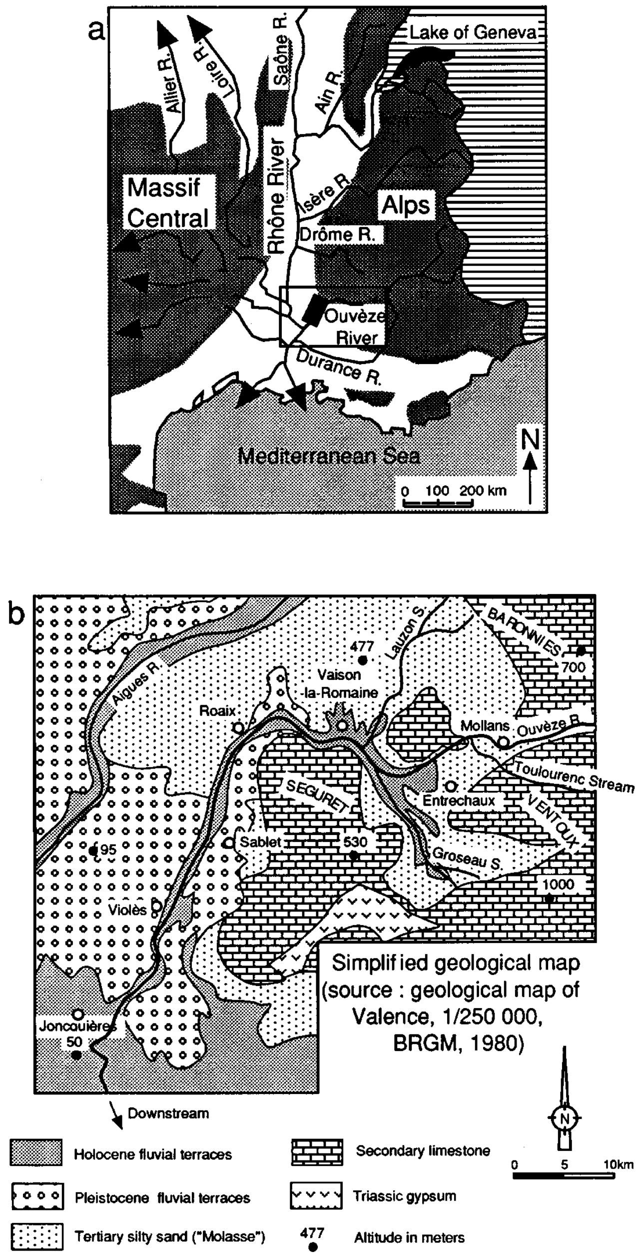

Figure 1. The Ouvèze River in southeast France (a) and the study reach (b)

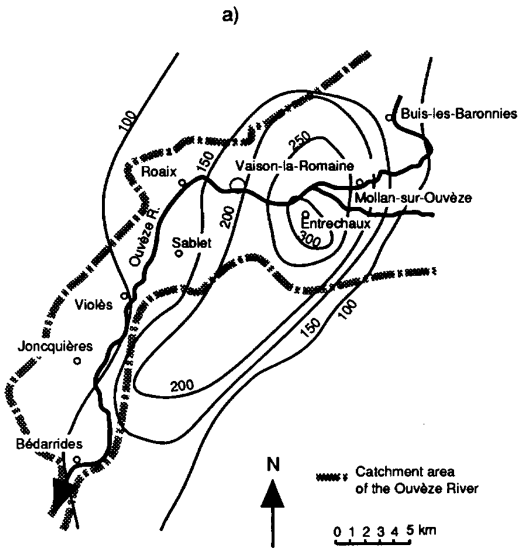

Figure 2. The 22 September rainfall distribution in the catchment area: (a) from rain gauge records (Blanchet and Deblaere, 1993); (b) from radar images (Kapfer, 1993)

STUDY AREA AND METHODS

General characteristics of the Ouvèze River

The Ouvèze is a sixth order piedmont river, 90 km long. The channel is braided with a cobble bedload (Figure 3). The river rises in the Baronnies Prealpine Massif and is joined by tributaries from the Ventoux massif (1909 m). These branches merge immediately upstream of Vaison. The alluvial floodplain, up to 500 m wide, is incised into Pleistocene river terraces (Figure 1b). Immediately above Vaison the gradient of the river is 0·006 to 0·010 mm^{-1}; in the studied reach, from Violès to 15 km downstream of Vaison, the slope is only 0·004 to 0·006 mm^{-1}.

The river hydrology is typical of medium altitude Mediterranean mountains. The annual average discharge is 5·2 $m^3 s^{-1}$ (1971–1993) for a catchment area of 586 km^2 (Figure 4a). Records since 1970 reveal that a peak flow of 220 $m^3 s^{-1}$ equates to the 1 in 10 year event (Figure 4b) but these records are too short to estimate periodicities for very large floods. The flood of 22 September cannot be reconciled with Gumbel analysis (Figure 4b). Myer’s coefficient for this flood is only 33 with a flow of 800 $m^3 s^{-1}$ at Vaison.

A wooded corridor isolates the river from the agricultural areas, where there are vineyards. This monoculture covers most of the floodplain. The pioneering vegetation of the river bed is *Polygonum persicaria* on gravel bars covered by silt, and *Calamagrostis* sp. and *Festuca* sp. on sand ridges (both grasses requiring water). Flat areas of high banks which are flooded in heavy rains are occupied by *Xanthium spinosum*. Alluvial wooded areas upstream have *Salix viminalis*, then *Salix incana* further downstream, then *Salix purpurea*. This succession gives way to ash units (*Alnus glutinosa*) on the wet silty soils of cutoffs. There are poplars (*Populus nigra*) on fixed gravel bars and *Populus alba* mixed with *Quercus pubescens* on low terraces (Nègre, 1980).

Methods

The influence of the flood on the spatial extension of the forest and the hydraulic behaviour of the forest during the flood were both studied.

Maps, aerial photographs and GIS. The ‘Napoleon’ land register established in 1836 and the ordnance survey map of the Vaison ‘Canton’, edited in 1857 at a scale of 1:40000, show the 19th century landscape pattern. There are also a series of aerial photographs which show changes in the elements or units of the countryside in 1947, 1971 and 1991. Additionally, the study of aerial photographs taken before and after the flood enabled the morphogenic and destructive activity of the flood to be established, as well as its effect on the

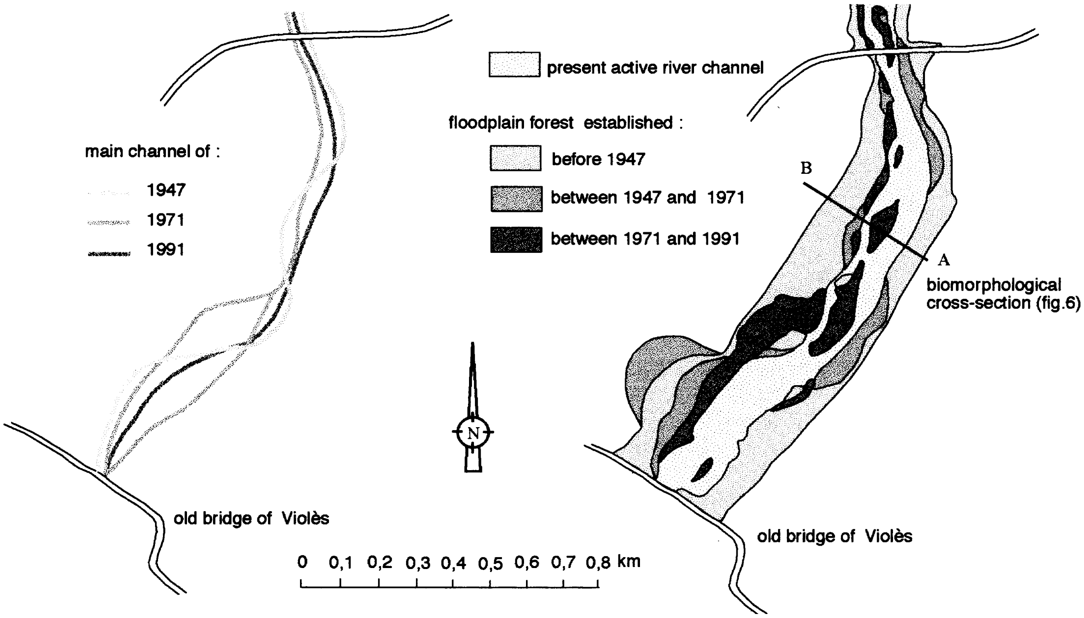

Figure 3. Historical dynamics of the active tract in the Violès site

spatial extension of the forest. A simplified map of the floodplain forest, standing or flattened, was determined from an IGN photographic flight in 1991 (scale 1:20000) and a special flight on 23 September 1992 (1:8000) between the Roaix and the Joncquières bridges along a 18 km reach. Both photographs were computerized (scanned, redrawn and rasterized) and superimposed to enable the production of a synthetic and dynamic map. This shows the spatial changes of the fluvial units between 1991 and 1992, which can be attributed to the flood of 22 September, since this flood was the only flood in that period (Figure 5a). One pixel, representing a 20 m square, is shown on the 1:34000 map. The Geographic Information System (GIS) used in this study enabled the areas of the different physiognomic units to be established. Also cross-sections allowed the measurement of the width of each physiognomic unit in 1991 and 1992. The values of each transect form a statistical population and the two different years can be compared (see Table I). For each cross-section, the width of the active tract before the flood was, for example, compared with the width of the forest units eroded by the flood or with units where the trees were merely flattened (Figures 5b and 5c).

Table I. Statistical results of the GIS surface analysis

	Before the flood (per ha)	After the flood (per ha)	Evolution rate (%)
Active tract	136	180	+32
Forest	306	228	–25
Flattened tree units	0	34	–
Total	442	442	–

Field sampling. A 280 m long cross-section was taken across the floodplain shown in Figure 3 (Figure 6). The following parameters were defined.

- Topographic: a cross-sectional profile showing heights was surveyed (Figure 6e). Micromorphological variability (*lm*) indicators have been included (Figure 6). For a given phytogeomorphological unit, the amplitude (*A*) and the length (*L*) of the surface undulations (*lm*=*A*/*L*) were used to construct a micromorphological index.
- Hydraulic: the flood level height, obtained from high water marks (Figure 6b), enabled the discharge and the stream power in the active tract to be evaluated. The longitudinal slope of flood peak water level was

estimated in the same way. Channel geometry, established from the topographical study (flood section and wetted perimeter) and the flood stage enabled the estimation of some discharge values and specific stream power values, in spite of a large margin of error caused by bed instability (Rotnicki, 1983; Bagnold, 1966).

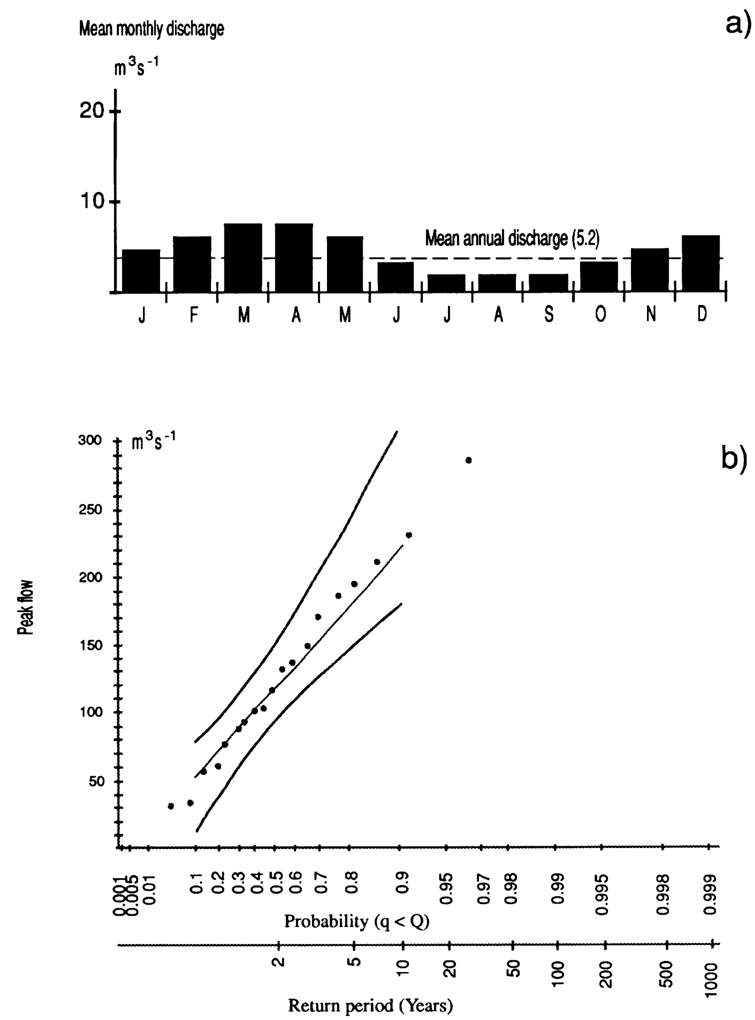

Figure 4. Mean monthly discharge (a) and peak flows (adjustment to Gumbel's law) (b) of the Ouvèze River at Vaison la Romaine (confidence interval with 90 per cent probability)

- Phytogeographic: the units of vegetation were distinguished (Figure 6a) and all the trees present on a 4 m wide strip, on each side of the cross-section were located laterally and their trunk diameters measured (Figure 6d). Tree species, including those flattened, were identified. The volume of coarse woody debris per hectare was determined (Figure 6c).
- Sedimentary: local sampling of the phytogeomorphological units enabled both a synchronic and a diachronic analysis to be carried out. The median of D_{50} of the surficial deposits (Figure 6g), the thickness of the recent sand deposits resulting from the flood of 22 September 1992 (Figure 6h) and the thickness of the older overflow silts (Figure 6i) were determined for 40 samples. At points α, β and χ in the riparian forest, six to eight samples were taken at intervals of 15 cm depth in the overflow deposits in order to establish the history of sedimentation (Figure 6j and 6a).

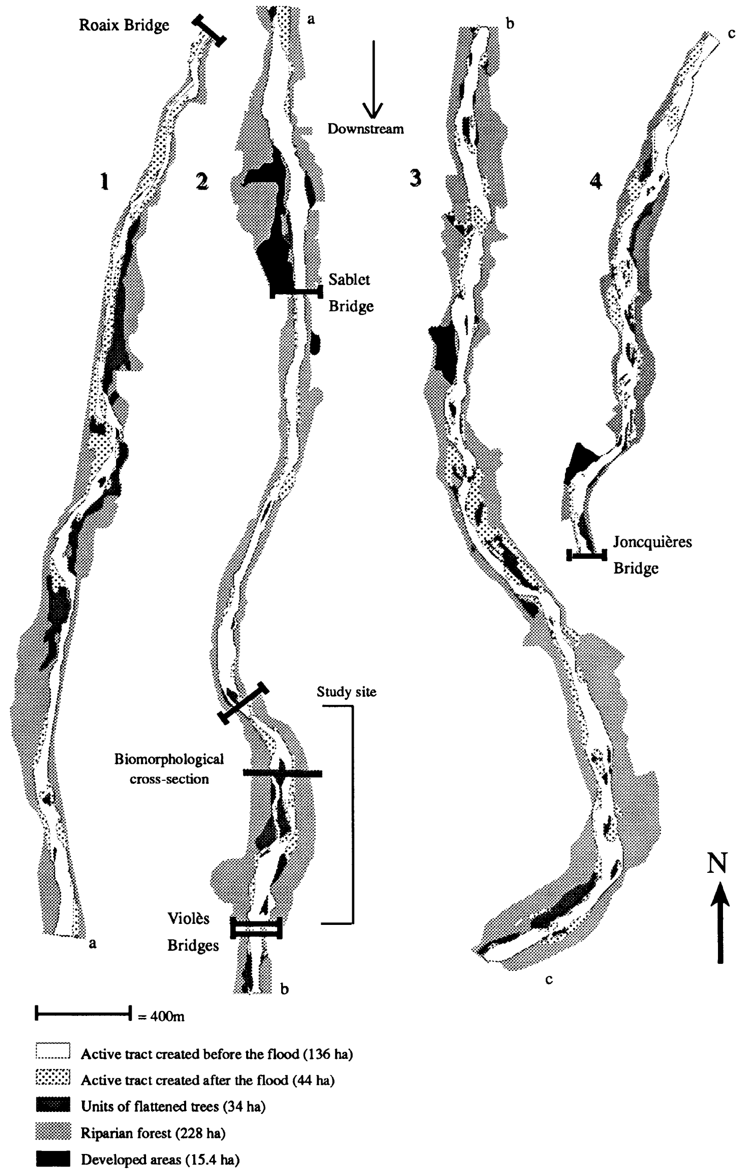

Figure 5.(a) The flood and the hydrosystem units, the GIS approach.

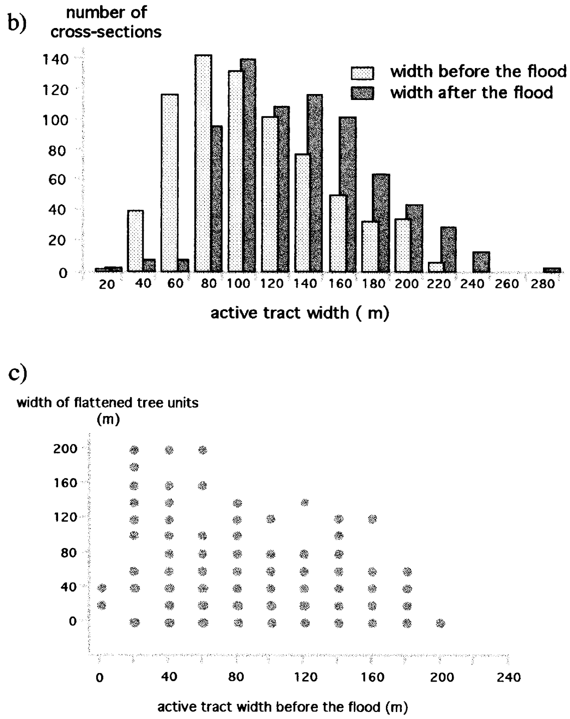

Figure 5. (b) The flood and the active tract width. (c) The units of flattened trees, no correlation with the width of the active tract of the river before the flood

RESULTS

The flood effects on the extension of the riparian forest

In the study reach, the flood increased the area of the active tract by 32 per cent. This increased from 136 to 180 ha by the destruction of the riparian forest. Also, 34 ha of pioneer vegetation was flattened by the flood; this was about 11 per cent of the original forest. Twenty-five per cent of this wooded area, i.e. 78 ha, was destroyed or considerably altered (Figure 5a). These results were greatly improved by statistical analysis carried out between the Roaix bridge and the Violès bridge; 745 cross-sections (pixel lines) were compared, and the margin of error was of the order of one pixel (20 m square).

Figure 5b shows that the width and the variations of the active tract increased considerably in the majority of the cross-sections. The average width and its standard deviation increased from 87 to 113 m respectively. It is now rare to find a channel width of less than 70 m. There is a clear break between the 60 m and 80 m ranges. Correlation is good between the original width (X) and the post-flood width (Y):

$$Y = 0{\cdot}8\,X + 42{\cdot}7$$
$$n = 745;\ r = 0{\cdot}78 \text{ and } p < 0{\cdot}0001.$$

For an active tract width of 45 m, the 400 year flood widened it to 80 m. Above a width of 200 m, no widening was observed.

Functions of riparian forest

The forest acted as a filter to the movement of water, sediment and organic material and thus reduced their morphogenic effectiveness.

First, for this type of event, it is apparent that the riparian forest filtered the hydrologic flow. The floodwater level in the active tract varied laterally. On the right bank, it decreased rapidly when it reached the forest. Similarly, the micromorphological index, which is very high at the forest edge, was reduced laterally.

Secondly, the forest also filtered coarse woody debris (Piégay, 1993). The interface between the forest and the active tract was the main zone of a characteristic debris line. The mass of coarse woody debris, estimated for this sector, was over 5000 t ha^{-1} but this reduced laterally to less than 5 t ha^{-1} when the sampling area was more than 40 m inside the forest.

Thirdly, the sedimentary load was rapidly trapped. On the right bank, the unvegetated gravel bar is higher than the overbank deposits of the floodplain. Thus it could have moved into the forest area but such movement was stopped in the first few metres of the wooded area. There was also a rapid reduction in the size of the fine sediment in these high-energy wooded banks. Beyond 25 m, values of D_{50} were comparable from one point to another (Figure 6g).

The three graphs (Figure 6j) show that the 400 year flood was rapidly filtered. The recent deposits are very coarse at point 'β', which is 6 m behind the debris line, and these size fractions contrast greatly with the older deposits. Also, the flood left a coarser deposit which was observed at the bottom of a borehole. In this area, the studied flood was thus a very important morphosedimentary event (Figure 6j). On the other hand, at points 'α' and 'χ' at 30 and 55 m respectively from the channel, the size of the recent flood deposits is similar or even finer than those of the older sediments. The accretion in the mature forest (the right bank forest is higher than the vineyard area) induced a similar reduction in the size of sediments. The evolution of the median sediment size (Figure 6j) for points 'α' and 'χ' shows that as sediment thickness increases, their granulometry decreases. The 1992 flood did not modify this trend; the granulometry of the last sediments, deposited on the leaf litter, was finer than the initial deposits. Consequently, in terms of sediments, the flood was not an exceptional phenomenon more than 40 m from the active tract.

Exceptional floods and diversification of vegetation units

The spatial position of vegetation units in the hydrosystem and their hydraulic roughness determine the amount of change from before to after the flood event.

In the Violès area, the study of mean particle size, with the exception of the distinction of the active tract and the floodplain, showed that particle size reduction was not a common phenomenon on the floodplain. In the riparian forest, the reduction occurred on the left bank but not on the right bank. This spatial difference also involved the woody debris line, the recent sand deposit and the positions of the flattened tree zones. This shows a hydrodynamic asymmetry in so far as, on the right bank, the floodplain area was subjected to the dominant flow during the flood, whereas the floodplain area on the opposite side was not. Figure 6 shows that the coarse woody debris tonnage (less than 10 t ha^{-1}) and the depth of flood deposits were negligible on the eastern zone (left bank). Even the forest edges were spared and no trees were flattened.

On the scale of the valley cross-section (in the reach between the Roaix bridge and the Violès bridge), the width of the flattened tree units was independent of the width of the active tract before the flood (correlation coefficient = 0·237; p 0·0001 (Figure 5c)). The riparian forest was therefore able to react in different ways to the flood waters for a given width of the channel. Specific characteristics of the riparian forest (tree density, diameter, species type) influenced its resistance capacity. The presence or absence of flexible pioneer stages could also be a major factor.

Thus flood waters, acting on a riparian forest in which the hydraulic roughness was extremely diverse, transformed the contact zone between the floodplain and the active tract. By destroying mature units, flattening the pioneer units, depositing very heterogeneous sediment sizes and producing different amounts of woody debris, the flood of 22 September 1992 increased the phytomorphological units, diversified the riparian zone and increased the complexity of vegetation patches. By occupying the boundary between the terrestrial and aquatic environments, the floodplain forest displayed phytomorphological processes which are both original and interactive. This makes this area a real ecotone.

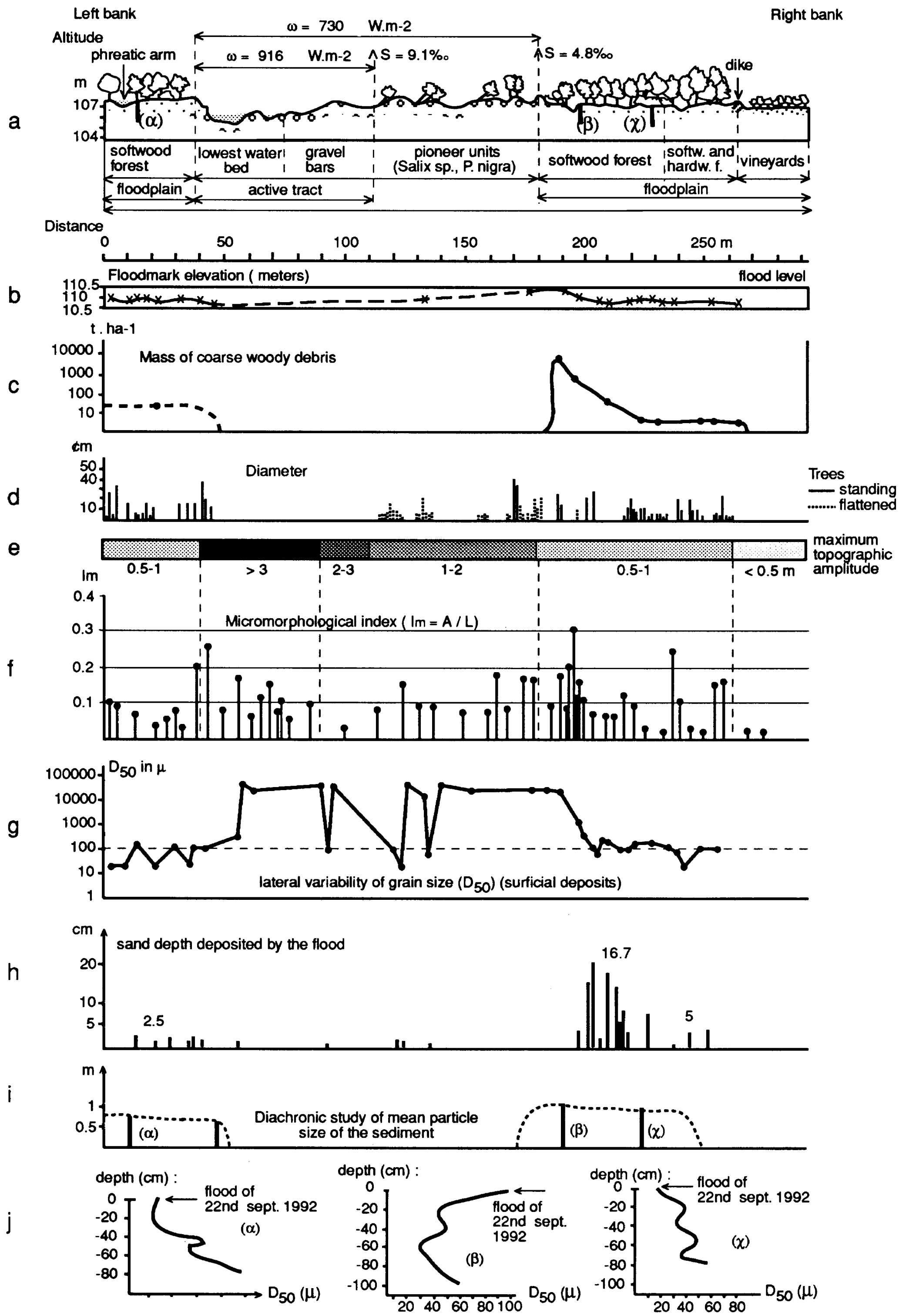

Figure 6. Cross-section of the Violès reach and transverse evolution of biomorphological descriptors (located on Figures 3 and 5a)

DISCUSSION

Riparian forest is a recent phenomenon in the Ouvèze River that greatly influences the mechanisms of important floods. It is now imperative to decide on a strategy to manage this resource.

Biometamorphosis, a response to human influence

In the last 50 years, wooded floodplain has become a major component in the Ouvèze system. In the last century this area was actively farmed. A study of the land registry for areas bordering the active tract of the Ouvèze River in the Mollans-sur-Ouvèze commune shows that in 1836 the land was 24 per cent meadows, 17 per cent cultivated land, 8 per cent vineyards/orchards, 30 per cent reedbeds and only 2 per cent forest. In 1857, the river bank between Entrechaux and Sablet on a stretch 13·5 km long showed 6 per cent meadows, 9 per cent vines, 64 per cent arable land compared to 19 per cent woodland and 2 per cent waste land. Since 1947, the area of the floodplain occupied by the forest has increased considerably at the expense of the active tract. This change took place from 1973 onwards (Figure 7). The average widths of the active tract and the forest changed from 83 and 50 m in 1947 to 48 and 92 m in 1991 respectively. At the same time the linkages between the two systems have been reduced. The pioneer stages, the interface between the active tract and the forest, the meandering of the channel and the number of wooded islands (Figure 7) have been reduced so that the system now tends to be composed of two parallel tracts with a reduced interface zone.

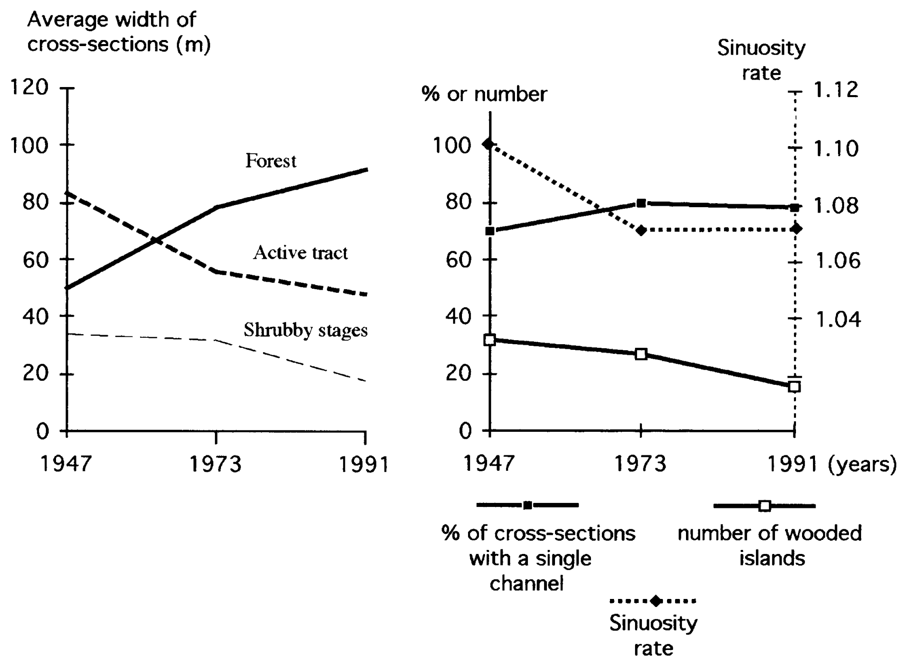

Figure 7. Historical changes of the riparian forest extension and the connectivity between it and the active tract

Similar changes have been documented in the Alps and the Alpine foreland but most of these changes are the result of river embankment (Bravard, 1985; Bravard and Peiry, 1993; Girel, 1994) or river regulation by hydroelectric reservoirs (Peiry and Vivian, 1994). As on some other rivers in the watershed of the Rhône, such as the Ardèche (Bravard *et al*., 1990; Piégay, 1995), there are two principal causes for the afforestation of the alluvial area of the Ouvèze river. The first, external to the reach, concerns changes in the catchment area over the last century. In general, there has been an attenuation of peak flows and a reduction in sedimentary transport. This can be attributed to reafforestation in the catchment (Combes *et al*., Cosandey, 1995). Also, in the catchment area, restoration work (reafforestation of more than 800 ha, the planting of grass, and regulation of the torrential stream tributaries by means of faggots and more than 1000 dry-stone-wall dams) was carried out

between 1895 and 1910–1914 (Mougin, 1931). A study of Napoleon land surveys shows a great increase in the reafforestation rate of the catchment area between 1831 and 1988 (Table II).

Table II. Evolution of the forested rate of the Ouvèze catchment area between 1830 and 1988

Forested rate (%)	Observation date	Source
20·6	1831	Land register of Napoléon I
24·0	1929	Oral report from the agricultural service
23·7	1931	After Mougins (1931)
33·0	1988	Local district inventory

The second cause, within the reach, is the modification of the floodplain by human activities. The riparian zones used to be integrated into the local agricultural economy because they were used for grazing and firewood. In the 19th century arable land reached the active tract but after 1945 the specialization of agriculture caused rural populations to abandon progressively riparian zones which were considered to be marginal and unprofitable. By 1947, the river flowed through an easily identifiable natural tract. This was occupied by a shrubby pioneer species (*Salix* sp. and *Populus alba*) which not only colonized the floodplain but also the edges of the active tract. When this vegetation reached the tree stage, it tended to reduce the width of the river (Hey, 1986).

The growth of the forest thus led to a form of fluvial metamorphosis (Schumm, 1977). An adjustment to the channel geometry acting on water and sediment discharges was caused by a modification of external factors (changing human occupation of the catchment area acts on the hydrologic and sediment fluxes which enter into the system) and internal factors (floodplain occupation changes affecting the active tract width) in the area under study. Although initiated by biological factors, this mechanism is an element in the dynamic equilibrium of the river. The concept of biometamorphosis (Piégay and Bravard, 1993) observed in the Ain, a piedmont river further north, can again be shown because a new biomorphological balance is being established by progressive and continuous biodynamic forces.

Biometamorphosis and flood control

Is the progressive extension of the riparian forest – a recent phenomenon – an aggravating factor for flood control?

By extending itself laterally and by building up the ground surface (more than 1 m thickness for the overflow deposits, up to 17 cm for the flood of 22 September), as well as increasing the hydraulic roughness, the forest has in fact considerably reduced the channel capacity to evacuate flood waters. The forest has channelized very rapid flows (water level slope 0·09 and velocity 3 m s^{-1}) into a narrow channel with a high potential for transport (the specific power is 900 W m^2 in the Violès reach). Where the wooded bank was insufficiently wide, the forest was totally destroyed and flows significantly modified the agricultural zones by surface erosion.

Conversely, the forest is beneficial with floods of lower magnitude which are characterized by the lateral extension of filtered flood waters. Agricultural zones upstream of riparian forest are protected and the progressive spreading of the water enables peak flows to be attenuated, thus reducing the downstream damage. Also, the riparian forest canalizes rapid flows into the active tract and only allows slow lateral extension of the flood waters, thereby reducing damage outside the active tract.

Riparian forest and fluvial hydrosystem management

Many active tracts in southeast France are being colonized by woody growth. This evolution, connected to rural history, should be taken into consideration in the management of these areas. Several functional attributes, useful for river management, have been selected.

1. Riparian forest reduces the morphological capacity of large floods by filtering flood waters in the wooded areas. Moreover it causes a build-up of the floodplain surface, reduces the active tract and thereby reduces the flow capacity of the active tract.

2. The riparian forest, periodically rejuvenated by floods, is a key area in the fluvial ecosystem. Biodiversity, both of species and of processes, is at a maximum in high-energy zones where there are dynamic linkages between the active tract and the floodplain (Naiman *et al*., 1993; Schnitzler-Lenoble and Carbiener, 1993).
3. Nevertheless, when the wooded alluvial areas increase, they become areas of great ecological value and minimum widths (from 5 to 50 m) have been proposed (Pinay and Décamps, 1988; Osborne and Kovacic, 1991). Despite the possible increase of the risk, some minimum wooded floodplain area should be defined scientifically and legally. Steps to conserve or to extend it should be taken when there are major ecological interests or where the wooded area would attenuate flood waters.

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